

COMBINING EXPERIMENTS AND FIELD SIMULATIONS IN A FIRST-YEAR ELECTROMAGNETISM COURSE

H. De Gersem, E. Temmerman, B. Van Damme, B. Vandewoestyne, T. Roggen

Katholieke Universiteit Leuven, Sciences, Engineering and Technology Group Campus Kortrijk,
Etienne Sabbelaan 53, 8500 Kortrijk, Belgium, Herbert.DeGersem@kuleuven-kortrijk.be

Abstract—First-year bachelor students carry out 3D magnetic field simulations and laboratory measurements on a simple single-phase transformer as part of an introductory course on electromagnetism. The students are instructed to compare analytical, numerical and experimental results and to discuss any discrepancies between them. The integrated laboratory is successful in linking electromagnetic field theory to a hands-on example.

I. INTRODUCTION

First-year courses on electromagnetism typically consist of lectures, exercises and laboratory experiments. Electromagnetic theory heavily relies upon the concept of scalar and vector *field* quantities. For that reason, a lot of field plots are shown during the *lectures*, not only for explaining the Maxwell laws but also for indicating the working principles of typical applications. In *exercises*, the Maxwell equations in integral form are applied to simple configurations. The corresponding field patterns are mostly trivial and uninteresting. Analytical field solutions (e.g. by solving the Laplacian for an electrostatic field) are part of more specialized courses on classical electrodynamics in further years. In the *laboratory sessions*, generally global parameters (voltages, currents, powers) are measured. Measuring electric or magnetic field distributions would take too much time. Hence, the field concepts taught in the lectures are almost absent in exercises and laboratory sessions. This problem has been alleviated partially by adding some simulation tasks [1]. Nevertheless, it remains difficult to establish the field idea as a common link between lectures, exercises, labs and simulations.

II. LABORATORY SETUP

We intend to concretize electromagnetic field theory using a practical example. An integrated lab session should deal with analytical formulae, numerical field simulation and measurements. The students should carry out the laboratory assignment independently within a limited time frame, thereby practising field interpretation for a real-world configuration.

A single-phase transformer has been considered as a feasible and interesting example (Fig. 1). Its technical relevance and simple geometry enable its use in a first-year bachelor course. Challenges are the 3D geometry and field distribution, the nonlinearity of the iron core,



Fig. 1. Single-phase transformer in the laboratory.

TABLE I
LUMPED PARAMETERS CALCULATED BY A STUDENT TEAM.

	analytical	measured	numerical
k ()	4.00	3.58	3.72
R_1 (Ω)	11.2	11.6	-
R_2 (Ω)	5.0	4.8	-
R_{Fe} (Ω)	-	750	910
L_h (mH)	35.7	32.2	33.3
$L_{\sigma 1}$ (mH)	1.3	2.4	1.7
$L'_{\sigma 2}$ (mH)	1.3	2.1	1.7

the appearance of several secondary effects (eddy currents, forces, noise), the solution of the AC circuits and the laboratory precautions for the short-circuit and load tests.

The students are asked to read an introductory text [2] on beforehand. Technical aspects (application, construction, parasitic effects) are mentioned but not emphasized as the course does not cover electrical engineering. The working principle has been explained in a lecture. Experience with AC circuit solving is gained in an exercise session. At the beginning of the lab session, the students are asked to take a look at the provided transformer parts, to assemble the transformer and to specify its nominal properties in a table. The task consists of determining the resistances and inductances of the individual coils and the parameters of the equivalent scheme of the transformer based on (a) analytical calculations, (b) numerical field simulations and (c) measurements. The participants should perform these three tasks in parallel. All relevant result tables have three columns where the different results can be listed aside of each other (Table I). Irrelevant or missing results are indicated by hyphens. The questions in the text and the tables for collecting all results invite the students to interact with each other and to compare the obtained results. The laboratory exercise takes two sessions of 2.5 hours. The transformer geometry requires 3D simulation. The students already got acquainted with CSTs

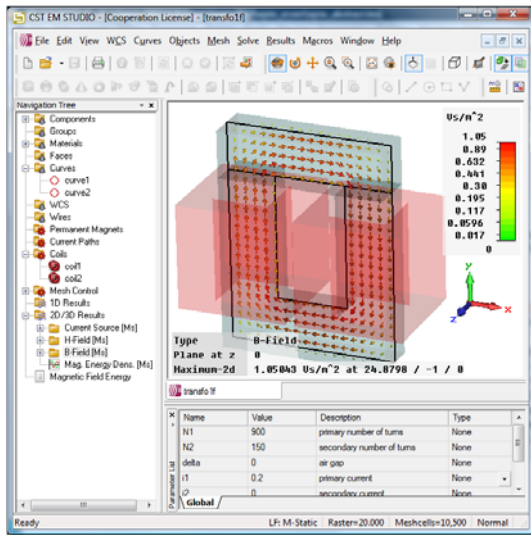


Fig. 2. Transformer model (simulation package CST EMStudio).

EMStudio [3] in two earlier simulation exercises. They succeed in constructing the model, defining the excitations, materials and boundary conditions and performing a first simulation in about an hour (Fig. 2). The students are evaluated on the basis of the completed tables and a short oral questioning.

III. TASKS AND INSTRUCTIONS

The inductances of the coils are measured without iron core, with iron core and after inserting air gaps between both core parts. The students compare the measured inductance values with analytical results (for an ideal solenoid) and with field simulations. First-year bachelor students occasionally make calculation and modelling errors. The comparative tables motivate them to detect and adjust mistakes themselves. Typically, the numerical results are more in line with the measurements than the analytical results. Small questions sound the students about the responsible assumptions underlying the analytical models. Some questions deal with the variations of the inductance according to the presence of an iron core and of air gaps.

The students observe noise when they apply an elevated current to the coils. This phenomenon is explained in the accompanying text [2]. The students are suggested to repeat the measurements for different air gaps. Analytical formulae relate the magnetic energy and the Maxwell force to the inductance variation. The forces are also calculated in the field simulation software. The analytical and numerical results for the dependence of the force on the air-gap length are plotted and compared.

Although the equivalent scheme (Fig. 3) of a single-phase transformer is not part of the course, the corresponding analytical formulae are derived and provided in order to calculate the lumped parameters from geometry and material data.

The *no-load test* is simulated by a nonlinear magnetostatic solver. Here, the attention is drawn on ferromagnetic saturation by calculating the electromotive forces for different current levels. A few questions trig-

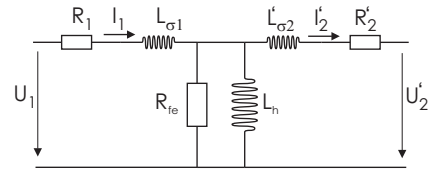


Fig. 3. Equivalent scheme of a single-phase transformer.

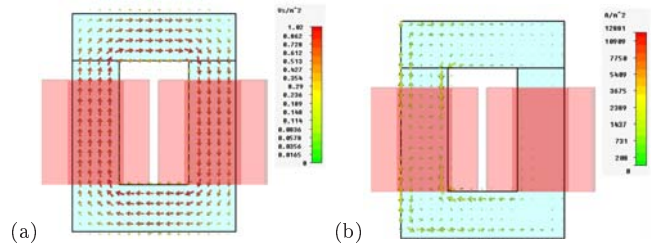


Fig. 4. (a) Magnetic flux and (b) eddy currents for the no-load test.

ger the student to carefully examine the field distribution (Fig. 4a). The coil resistances and the inductance matrix is used to compute the no-load current according to the nominal voltage.

The *short-circuit test* is simulated by a linear time-harmonic solver. A few questions invite the students to compare the no-load and short-circuit field patterns and to explain any disagreements. The short-circuit simulations are carried out before the measurements in order to point the students on the magnitude of the computed secondary current and to ask for precautions before switching on the experimental setup.

The necessity for laminating the core is explained in the introductory text. The individual laminations are visible. The equivalent circuit can accommodate for the eddy-current effect by an additional resistance R_{fe} , although a corresponding analytical model is missing. The eddy-current effect is easily introduced in the field model by means of an anisotropic bulk material. The students have to determine the equivalent permeabilities and conductivities of the homogenized material. The simulated losses are compared with the measured ones. Both allow the calculation of R_{fe} .

IV. CONCLUSIONS

The integrated laboratory exercise on a single-phase transformer makes the students familiar with the process of identifying appropriate assumptions and simplifying a real-world example to a model at which analytical formulae or numerical simulation can be applied. The fact that simulated field distributions for a realistic transformer model appear on a computer next to the corresponding measurement setup supports the teaching of the magnetic field concept.

REFERENCES

- [1] D. Lowther and E. Freeman, "A new approach to using simulation software in the electromagnetics curriculum," *IEEE Transactions on Education*, vol. 36, pp. 219–222, May 1993.
- [2] H. De Gersem, E. Temmerman, B. Van Damme, B. Vandewoestyne, and T. Roggen, "Measuring and simulating a single-phase transformer." http://www.kuleuven-kortrijk.be/~u0005424/labtrf_english.pdf.
- [3] CST AG, "EMStudio." <http://www.cst.com>.